AD-A062802

(1)

R-977

INERTIAL NAVIGATION SYSTEM STANDARDIZED SOFTWARE DEVELOPMENT

FINAL TECHNICAL REPORT

Volume I of IV

INTRODUCTION AND SUMMARY

June 1976

The Charles Stark Draper Laboratory, Inc.
Cambridge, Massachusetts 02139

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER R-977	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) INERTIAL NAVIGATION SYSTEM STANDARDIZED SOFTWARE DEVELOPMENT, FINAL TECHNICAL REPORT, VOLUME I, INTRODUCTION AND SUMMARY		5. TYPE OF REPORT & PERIOD COVERED 3/15/76-4/30/76
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) J. Sciegienny, R. Nurse, J. Wexler, P. Kampion		8. CONTRACT OR GRANT NUMBER(s) F33615-75-C-1149
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Charles Stark Draper Laboratory, Inc. 68 Albany Street Cambridge, Massachusetts 02139		10. PROGRAM ELEMENT PROJECT TASK AREA & WORK UNIT NUMBERS Task 4.2.1
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Avionics Laboratory Wright-Patterson Air Force Base Dayton, Ohio 45433		12. REPORT DATE June 1976
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

NTIS	White Section	X
DDC	Buff Section	☐
UNANNOUNCED		☐
JUSTIFICATION		
BY		
DISTRIBUTION/AVAILABILITY CODES		
Dist	AVAIL. and/or SPECIAL	
A		

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Inertial Navigation
Computer Algorithms
Computation Errors

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A navigation software simulation program was developed, checked and verified as a part of an investigation into the feasibility of standardization of software for aircraft Inertial Navigation Systems (INS). The program can be used to simulate the unaided INS navigation errors resulting from a partiular mechanization of the navigation equations on a given digital computer.

Technical data required for the Simulator Program design was obtained from survey of typical INS navigation software. The survey results revealed

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. Abstract (continued)

commonality in navigation computations employed in various INS configurations, the gravity models approximations used in the computations, the commonality in the frames and the transformations symbology employed in the computations and the software interface between the INS computations and the Avionics-System computations.

The navigation software simulation program is coded in Fortran IV for use on either IBM-360 or CDC-6600 computers.

The report is comprised of four volumes:

Volume I Introduction and Summary

Volume II INS Survey and Analytical Development

Volume III Program Description and User's Guide

Volume IV Program Listings

R-977

INERTIAL NAVIGATION SYSTEM STANDARDIZED SOFTWARE DEVELOPMENT

FINAL TECHNICAL REPORT

VOLUME I

Introduction and Summary

June 1976

Approved: W.G. Denhard
W. G. Denhard

The Charles Stark Draper Laboratory, Inc.

Cambridge, Massachusetts 02139

ACKNOWLEDGEMENT

This four-volume report was prepared under USAF Contract F33615-75-C-1149 by Charles Stark Draper Laboratory, Inc., Cambridge, Massachusetts, in accordance with Section 4 of the contract. The monitoring Air Force project engineer is Captain E. Harrington (RWA-2), Air Force Avionics Laboratory, Dayton, Ohio.

The Draper Laboratory Program Manager for this task is Dr. George T. Schmidt and the Lead Engineer is Arthur Ciccolo. The coordinator of this report is Janusz Sciegienny and the authors are Janusz Sciegienny, Roy Nurse, Peter Kampion and John Wexler.

The authors express their appreciation to Mr. W. Shephard, Mr. D. Kaiser and Mr. Stan Musick of the Air Force Avionics Laboratory for their assistance during the course of this contract.

FOREWORD

- This Final Technical Report, as outlined in Section 1.0 of Volume I, primarily addresses itself to the development of a computer program which simulates the outputs of an ideal inertial measuring unit (IMU) and emulates the operation of the airborne navigation computer producing the earth-referenced position, velocity, and attitude outputs.

- The use of this program to define a Standard Navigation Algorithm for a moderate accuracy, gimballed, local vertical Inertial Navigation System (INS) is illustrated in an Addendum to this report, where an F4 combat interdiction mission is simulated using both the "baseline" software and "upgraded" version of the navigation software described in Volume II. Critical parameters for both the inertial measuring unit and the navigation computer such as quantization and word length and structure, were selected to be compatible with the application.

- The "baseline" software is shown to be eminently suitable for use in a moderate accuracy INS and may be considered to constitute a Standard Navigation Algorithm for the F4 mission, since the computational errors contribute less than 0.1 nautical miles error per hour to the total INS errors.

- The "upgraded" software is suitable for higher accuracy, longer duration applications.

VOLUME I

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1.0 INTRODUCTION

The objective of this task is the development of a computer program which will enable the user to select and evaluate proposed, "standard" navigation software modules for use in any aircraft inertial navigation systems (INS). Exploitation of such a program would ultimately permit the Air Force to specify proven, standardized INS software for any new system, mission, or accuracy requirement. The cost savings, resulting from employment of such standard navigation software as GFE, would be considerable.

This task, begun in late spring 1975, was first directed toward the definition of standardized symbology, coordinate frames and transformations for any type of inertial measuring unit (IMU) - gimballed or strapdown. A single computational frame was selected and a "baseline" set of standard navigation equations was developed. These equations were incorporated into a computer program which enables the user to evaluate the resultant navigation performance over a user-specified aircraft mission. Upgraded equations were added to the "flight code" portion of the program to permit improved performance - again as user options.

Technical data required for implementation of the above efforts were obtained by performing a survey of typical aircraft INS software. External constraints on the navigation (and attitude) software were determined by performing a second survey of the software interfaces between the navigation computer and the other avionics subsystems.

The results of these efforts are presented in four volumes, comprising the Final Engineering Report:

Volume I contains the summary and conclusions.

Volume II contains:

(a) The results of a survey of INS navigation computations

(b) The development of the "standard" navigation equations

(c) The results of a survey of the INS navigation software interfaces with other avionics subsystems

(d) The definition of symbology, conventions, coordinate frames, transformations, and selection of the computation frame.

Volume III contains a detailed description of the numerical simulator program (NUMSIM), and a user's guide.

Volume IV contains the listings of NUMSIM and its variable precision version, VUMSIM.

2.0 SUMMARY AND CONCLUSIONS

2.1 Development of Standard Modular Navigation Software

Based on the survey of aircraft navigation equations, and utilizing the selected (local vertical wander azimuth or LVWA) computational frame, the navigation equations for earth-referenced inertial navigation are developed, in the standard symbology.

The core of these equations is the "standard" navigation algorithm. This is a set of difference equations which accepts as inputs the integrals of specific force in the (LVWA) computational frame and an externally derived altitude reference. The outputs of the "standard" navigation algorithm are the geodetic latitude, longitude, altitude, the wander angle, the angular velocities of the computation frame with respect to the inertial frame in computational frame coordinates, and the north, east and vertical velocities. (The long term altitude (vertical velocity) tracks the external reference while the short term reflects the inertial system characteristics). These core equations are the same regardless of the inertial measuring unit (IMU) configuration or mechanization-gimballed or strapdown, space-stabilized or local vertical.

The basic form of the "standard" algorithm, which corresponds closely to the software mechanizations of several of the surveyed moderate accuracy, local vertical INS - but employing the standard symbology, conventions, and nomenclature - is called the "baseline" algorithm.

A more precise form of the "standard" algorithm is called the "upgraded" algorithm (Figure 2-10). It consists of the minimum modifications to the standard algorthm required to reduce the computational errors with respect to the reference (PROFGEN) by at least an order of magnitude. These modifications included replacing some approximate expressions in the "baseline" algorithms by exact expressions or better approximations, by repeating certain computaions, and by introducing a small amount of interpolation and extrapolation--where the improvement in computational accuracy was apparent. The WGS72 Ellipsoidal Earth gravity model was employed

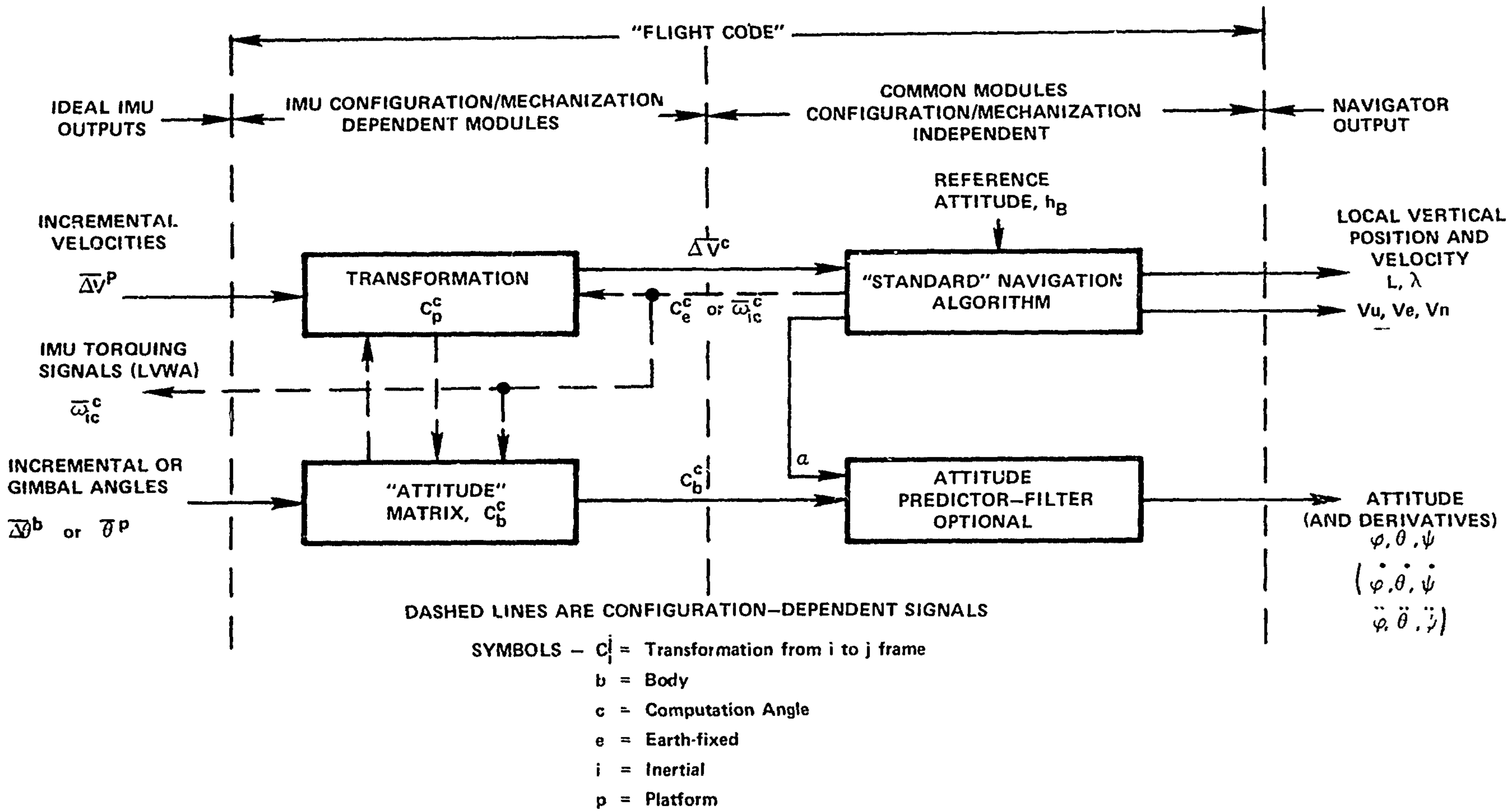

Figure 2-1. Standard Modular Navigation Software "Flight Code" Modules

in both algorithms, per AFAL direction, although its use is not mandated for the "baseline" algorithm. The "standard" navigation algorithm described above constitutes one of the standard INS software modules in the simulator program.

Attitude computation may be considered to comprise a second module. The inputs to the attitude module are the aircraft body-to-computational frame transformation and the wander angle. The outputs are the aircraft roll, pitch, and heading. If the optional attitude predictor-filter is included, the outputs will be the filtered predicted values of: roll, pitch, and heading; roll rate, pitch rate, and heading rate; and the related angular accelerations. The attitude module is also configuration/mechanization invariant.

The remaining two modules - the transformation and the "attitude" matrix modules - are IMU configuration/mechanization dependent, i.e. they differ with configuration - strapdown or gimballed, and with mechanization (in the latter case) - space stable or local vertical.

The transformation module generates and updates the rotation matrix relating the IMU frame to the LVWA computational frame. For a LVWA IMU, the transformation is completely trivial - an identity matrix. For a space-stable IMU, the transformation is non-trivial and involves the successive transformations from: the IMU frame to the inertial reference frame, hence to an earth-fixed equatorial-polar frame, and finally to the LVWA computational frame. The angular rates involved are moderate and the transformations are normally updated once per navigation computation cycle (4 to 16 Hz). For a strapdown IMU the transformation from the aircraft body frame to the LVWA computational frame is complex and involves both the angular velocities of the body frame and the LVWA computational frame with respect to the inertial reference frame. Due to high body rates (up to 400 degrees per second) this transformation must be updated very frequently (32 to 128 Hz). However, the transformation required for the incremental velocities is precisely the "attitude" matrix needed for attitude computation. Hence this combined module is frequently called the "(incremental) velocity/attitude algorithm".

The "attitude" matrix module for both the LVWA and SS IMU's involves the generation of a gimbal angle matrix (body-to-IMU transformation) from the gimbal angle encoders. For a LVWA system, the gimbal angle matrix is the "attitude" matrix. For a SS system, the gimbal angle matrix must be premultiplied by the IMU-to-computational frame transformation (as used in the transformation module) to obtain the "attitude" matrix.

Analytical development of the aforementioned modules is presented in Volume II, and the resulting software routines are described in Volume III.

2.2 Design of the Numerical Simulator Program

The purpose of the numerical simulator is to facilitate the evaluation of the numerical accuracy or to study the computational error propagation of a selected subset of proposed standard navigation software modules, appropriate to a specified type of IMU, when mechanized in a particular airborne computer, over a suitable aircraft mission profile.

The subset of software modules is selectable by the user and range from the "baseline" algorithms through several steps to the most sophisticated "upgraded" algorithms.

The type of IMU simulated may represent a local vertical, wander azimuth (LVWA), four gimbal platform, a four gimbal, space-stabilized platform, or a strapdown inertial sensor assembly with orthogonal components. In any case, a LVWA computational frame is employed.

The airborne computer characteristics include the length and structure of the floating-point word, the use of rounding or truncation in arithmetic operations, and the length of the computation cycles for navigation and attitude. Suitable (airborne computer) library routines for sine-cosine, arc-tangent and square root are implemented for the word length chosen.

The aircraft mission profile-time histories of position, velocity, attitude, specific force, etc. - is provided by an AFAL-supplied program called PROFGEN, which integrated the kinematic equations of a point mass vehicle performing coordinated maneuvers. It should be noted that the same profile may be used with any IMU type.

Quantization of IMU outputs (and of gyro torquing signals in the case of a LVWA IMU) may be specified by the user as desired. Except for the simulated gimbal angle encoder outputs (in the case of gimballed platforms), there is not cumulative truncation due to quantization..

The numerical simulator program is designed to provide the maximum flexibility to the user with the minimum amount of input from the user. For instance, to simulate a strapdown navigator, one parameter (IMUTYP=3) configures the IMU simulator, which provides outputs of incremental velocity and angles in the body frame to the simulated navigation computer ("flight code"), which, in turn, is configured of an appropriate subset of the standard navigation modules. Within these modules the user has several other options controlled by additional user-specified parameters such as whether to use a quaternion or a direction cosine matrix update of the body to computational frame transformation in the "velocity attitude" algorithm, what order of update to use, and how often to normalize (or orthonormalize) the result.

A functional block diagram of the numerical simulator program (NUMSIM) is shown in Figure 2-2. The profile generator program (PROFGEN) provides both inputs to the IMU simulator portion of NUMSUM and a reference with which the simulated navigation computer outputs are compared to obtain the computationally induced navigation and attitude error time histories.

An operational block diagram of the numerical simulator program is shown in Figure 2-3. From this figure it is evident that a single PROFGEN output tape may be used to drive any number of NUMSIM runs, provided only that the output frequency of PROFGEN corresponds to the shortest computational cycle employed in NUMSIM. The original intent of this task was to use such an AFAL-generated, PROFGEN output tape (in IBM-compatible format) to drive NUMSIM. This proved impractical, and several versions of PROFGEN were converted for IBM-360 operation at CSDL.

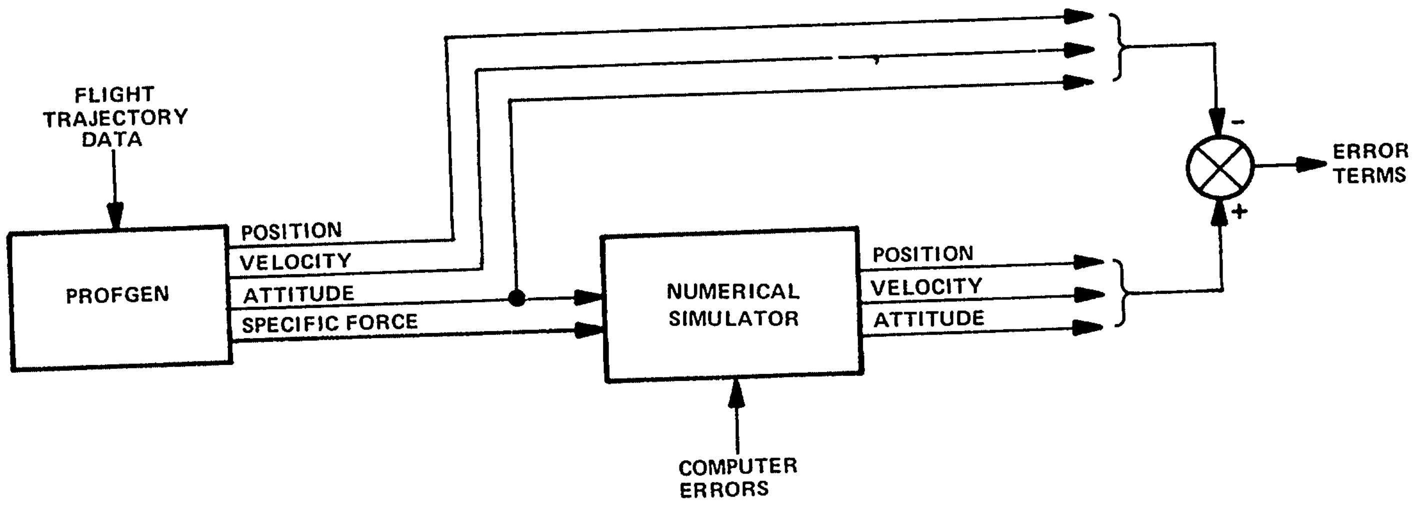

Figure 2-2. Numerical Simulation Program - Functional Block Diagram

SS 11/75-122

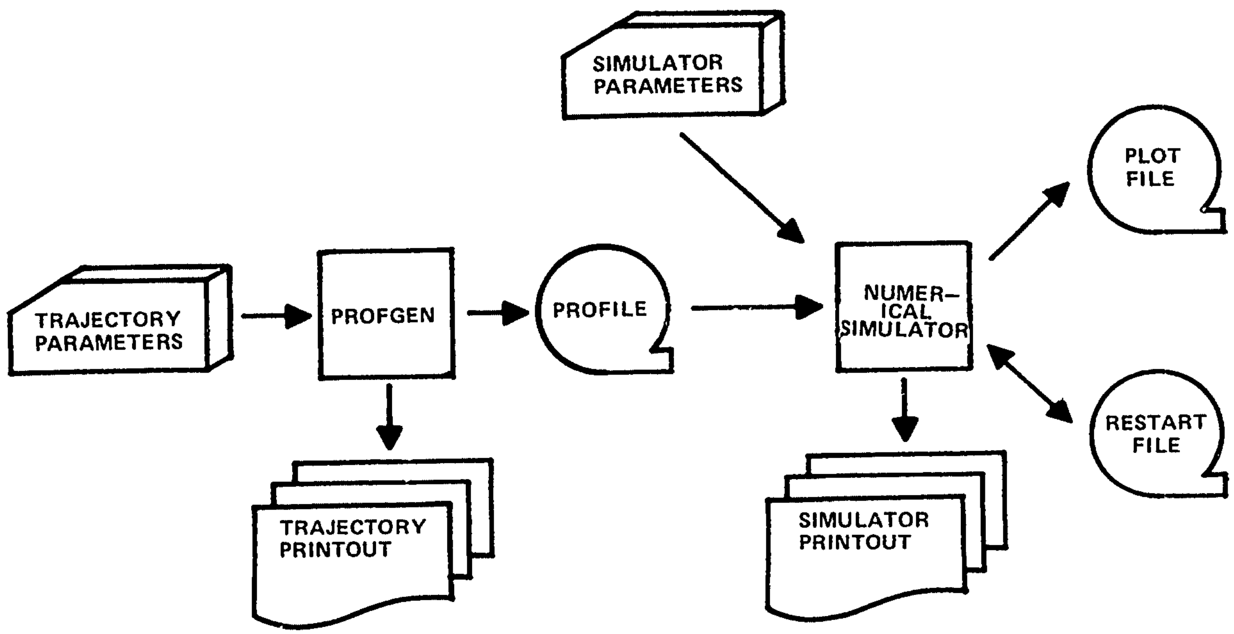

Figure 2-3. Numerical Simulation Program - Operational Block Diagram

SS 11/75-120

The numerical simulator was written in Fortran for the IBM-360 for use with the converted PROFGEN. Verification of NUMSIM was accomplished by noting that its outputs--using "upgraded" algorithms, short computation cycle, full word length, and no quantization--were negligibly different from the reference. NUMSIM (and its variable precision version, VUMSIM) were converted, installed and verified on the AFAL CDC-6600.

A detailed description of NUMSIM, including a user's guide, is presented in Volume III of this report.

2.3 Selection of Computational Frame

For any type of INS configuration, the navigation computations could be performed either in the local-level or in the space-stabilized computational frame.

The local-level geodetic wander-azimuth frame was selected as a computational frame for the INS computer errors simulation program. The frame selection was dictated primarily by the simpler computation format for the INS with a local-level stabilized platform and simpler software interfaces with most avionics and navigation-aid measurements. Computations in the space-stabilized frame are, however, somewhat simpler for the space-stabilized and strapdown INS.

The criteria used in the computational frame selection are presented in Volume II Section 5 of this report and are summarized in Table 2-1.

2.4 Selection of Standardized Frame Symbology

The survey of INS navigation computations described in Volume II, Section 1 of this report revealed a lack of commonality in the definition of axes frames and coordinate transformations used during navigation computations of various INS. Even the same types of INS employed on different aircraft use different definitions of the axes during navigation computations.

A consistent unambiguous set of frames and transformations based on the Honeywell conventions used in the SPN/GEANS[1] equations has been selected for the standardized frame and transformation definitions. The proposed standardized notation for use in the designation of the frames and the transformations is presented in Volume II, Section 6 of this report.

Table 2-1. Comparison of local-level and space-stabilized computational frames.

SELECTION CRITERIA	COMPUTATIONAL-FRAME CHARACTERISTICS	
	LOCAL-LEVEL	SPACE-STABILIZED
World-Wide Navigation	Requires wander-azimuth, free-azimuth, unipolar or inverse coordinates.	No added requirements.
Commonality of Computations for Various INS Configurations	Requires additional transformations in attitude computations for space-stabilized and strapdown INS.	Requires some additional transformations.
Complexity of Computations	Simpler computations for local-level INS.	Simpler computations for space-stabilized and strapdown INS.
Interface with Other Avionics Computations	Simpler interface with most avionics and navigation-aid computations.	Simpler interface with some (star-tracker) navigation-aid computations.

2.5 Survey of INS Navigation Computations

A survey of navigation computation mechanization employed in representative types of INS was initiated to investigate the following computation characteristics:

a. Commonality in navigation computations mechanization among various INS types.

b. Form of gravity models employed in the navigation computations.

c. Detailed form of the navigation equations mechanization.

d. Commonality of coordinate frames and coordinate transformations symbology employed in the navigation equations.

The survey included INS with a local-level stabilized platform, with a space-stabilized platform, and with strapdown configurations. The surveyed INS used either the local-level or the space-stabilized computational frame during the INS navigation computations. Table 2-2 contains a list of the surveyed INS, the type of platform stabilization, and the type of computational frame used during the navigation computations.

Table 2-2. List of surveyed INS.

INS	TYPE OF PLATFORM STABILIZATION	NAVIGATIONAL COMPUTATIONAL FRAME USED
KT-73	Local-Level geodetic	North-pointing below 70° latitude Wander-azimuth above 70° latitude
LN-15	Local-level geodetic wander-azmiuth	Local-level geodetic wander-azimuth
H-386	Local-level free-azimuth	Local-level free-azimuth geocentric
Carousel	Local-level free-azimuth rotating-level gyros and accelerometers	Local-level geodetic free-azimuth
GEANS	Space-stabilized	Space-stabilized
SIGN III	Strapdown	Local-level geocentric
SIRU	Strapdown	Local-level geodetic

The survey of the navigation computations employed by the INS with a local-level platform stabilization revealed the following commonality of computations:

(1) World-wide navigation computations capability.

(2) Use of barometric altimeter data to bound the vertical channel computation errors.

(3) Use of a direction cosine transformation matrix from the platform frame to the earth fixed frame in position computations.

The only surveyed INS with a space stabilized platform (GEANS) uses barometric altimeter data of the acceleration and the velocity levels.

The two surveyed strapdown INS (SIGN III and SIRU) employed a local-level, north-pointing computational frame not suitable for navigation in the polar regions. The coordinate transformation from the body frame to the computational frame is expressed by a quaternion rather than by the direction-cosine matrix.

The form of gravity model approximations employed in the navigation computations of the surveyed local-level platform stabilized INS results in the computed gravity error of the order of 20μg, which is comparable with the magnitude of the gravity anomalies. In GEANS navigation computations the gravity is computed with 0.1μg accuracy. The SIGN III uses gravity model computations with an accuracy comparable to the accuracy employed in the local-level INS computations. The SIRU uses a constant gravity value.

The survey results were used in design of the computer error simulation program. The survey results are presented in Volume II, Section 1 of this report.

2.6 Survey of the INS Software Interface, with Non-Inertial Computations.

A survey of software interfaces between the INS navigation computations and the avionics-system computations was performed to meet the following objectives:

(1) To determine the accuracy, the resolution, and the data rate of the inertially sensed data required for the avionics computations.

(2) To determine typical parameters of the navigation aids used in the INS navigation-computation updating.

The inertially sensed data consists of linear acceleration, attitude, and possibly attitude rate. The velocity and position are derived from the inertially sensed data. The linear acceleration data sensed by the accelerometers, is in the form of pulses representing velocity increments. The attitude data is obtained from the gimbal-angle readout. The attitude rate data is obtained either by differentiation of the attitude data, or it is sensed directly by the body-mounted (strapdown) rate gyros.

The typical navigation aids consist of the air data sensors, the Doppler radar, the Loran receiver, the Tacan receiver, the Omega receiver, the satelite based instrumentation, the multimode radar, the star tracker and the visual position fix instrumentation.

The following avionics computations are included in this survey:

(1) A-7D INS weapon-delivery computations.

(2) A-7D steering compuations.

(3) A-7D INS navigation displays.

(4) A-7D INS air-data computations.

(5) C-5 INS navigation-computation updating.

(6) Electronically Agile Radar (EAR) radar-antenna motion-compensation computations.

The survey results indicate the severe resolution and rate requirements for linear acceleration and attitude data are imposed by the antenna motion-compensation computations used in Synthetic Aperture Radar (SAR) operation. The required velocity-increment resolution is 0.00125 foot per second with a data rate of 256 Hz for an acceleration range of $\pm$ 2 g. The required level indication resolution is 40 arcseconds (1σ), and the required attitude data rate is 256 Hz. However, the data-rate requirements can be met by using the raw inertial sensor data to interpolate between 8-Hz navigation-computation updates.

The A-7D navigation computations use a 0.032-ft/s resolution of the velocity increment with a data rate of 5 Hz for an acceleration range of 10^{-2} to 10 g.

The A-7D weapon-delivery computations require the velocity increment data in the navigation frame with the data rate of 25 Hz. The required attitude resolution is 2 arcminutes (1σ) with a data rate of 25 Hz.

The A-7D steering compuations require velocity increment data in the aircraft-body frame with a data rate of 50 to 100 Hz for an acceleration range of 10^{-2}g to 10g.

The resolution and data rate of the inertially derived data required for the navigation and weapon delivery computations are adequate for the A-7D navigation displays.

The A-7D navigation computations use barometric altitude data to stabilize the vertical-channel computations. Tne air-data computer (ADC) is used to generate the barometric altitude data, the true and indicated airspeed data, and the Mach number data. The true airspeed data is used in computing the wind velocity. The indicated airspeed data is used for the head-up display (HUD). The Mach number is used in the weapon-delivery and in the automatic-flight-control computations. The 1σ accuracy of the ADC generated data is 0.25% attitude, 1 knot airspeed and 0.01 Mach number.

A survey of the navigation updating by the navigation aids in the C-5 indicates that the sampling rate of measurements is of the order of one sample per second and the updating cycle of the Kalman filter is of the order of a few minutes. The navigation-aid measurements provide an update of the computed position, velocity, and attitude. The measurements are also used to update the three gyro biases, the vertical accelerometer scale factor, and the barometric altimeter bias. The accuracy (1σ values) of typical navigation-aid measurements (other than satelite derived measurements) is on the order of 350 feet in position, 0.1 percent in velocity and 0.1 percent in altitude.

The survey results are used in selection of the input parameters for the computer error simulation follow-on runs, not covered in this report. The survey results are presented in Volume II, Section 4 of this report.

REFERENCES

1. Computer Program Development Specification for the Standard Precision Navigator/GEANS Inertial Navigation System (Configuration Item Number DQG8156A1) 4th Preliminary Issue, (no author named), Honeywell, Inc., St. Petersburg, Fla., 1 September 1974.

R-977

VOLUME I

DISTRIBUTION LIST

Internal		External
R. Bumstead	L. W. Torrey	Air Force Avionics Laboratory (20) Attn: RWA-3 Wright-Patterson Air Force Base, Ohio 45433
W. Caffery	R. Wexler	
A. Ciccolo	TIC (5)	
A. Coate		Air Force Avionics Laboratory (20) Attn: Capt. E. Harrington, RWA-2 Wright-Patterson Air Force Base, Ohio 45433
R. Crisp		
K. Daly		
M. Dare		
W. Delaney		
J. DiSorbo		
P. Dogan		
K. Fertig		
J. Fish		
J. Harper		
R. Harris		
J. Hursh		
P. Kampion		
J. Kishel		
W. Koenigsberg		
R. Leger		
R. Marshall		
B. McCoy		
W. McFarland		
N. Nathan		
R. Nurse		
P. Peck		
T. Reed		
D. Riegsecker		
O. Rye		
G. Schmidt (2)		
J. Sciegienny (2)		
R. Setterlund		